Falling Short But Not Falling Down: Challenges and Solution for the Service-Life Estimation of Gradually Degrading Bridges


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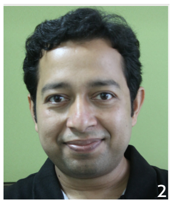
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Abstract: The failure of structural/infrastructural systems has significant societal and human consequences. Therefore, there is a crucial need to assess the structural condition of in-service and ageing structures, which is a major cost and management consideration. However, a typical structural condition assessment produces very subjective and highly variable results. This can be attributed to the variability in deterioration phenomenon, the presence of uncertainty in structural measurements, as well as the lack of good predictive models capable of considering those uncertainties in their analytical procedures. Further, neither the predictive models nor the condition assessment, alone can provide a comprehensive understanding of how a bridge is expected to deteriorate over its lifetime. In order to be able to predict the service-life of a degrading bridge, a probabilistic framework combining the predictive capability of the theoretical degradation model and the data obtained from NDT/SHM is necessary.

Background

The economic progress and sustainable development of our society need to rely on reliable and durable civil engineering structures and infrastructure facilities. However, such facilities, owing to their inherent vulnerability, are at risk from ageing, fatigue, and degradation processes resulting from aggressive chemical attacks and other physical damage mechanisms [1]. Old infrastructure is undergoing deterioration faster than predicted, because the mechanism of degradation was not understood well at the time of construction and was not taken into account in the planning [2].

The possible economic and social impact of ageing and deterioration processes of our infrastructure is exceptionally high, particularly for bridges. The I-35W bridge collapse in Minnesota, USA in 2007 had 13 people killed and 145 injured. According to the Minnesota DOT this incident impacted 140,000 vehicles daily and costed USD 400,000 per day due to the unavailability of the bridge and rerouting of the traffic. The economic losses to the region were USD 17 mn in 2007 and USD 43 mn in 2008. Back home, the Savitri river bridge collapse in South West Maharashtra in 2016 resulted in 26 casualties and 14 people being missing. The economic impact is yet to be properly estimated. These collapses were sudden and without any warning. Because of the sudden nature of these crises, the public often does not have a chance to prepare physically or mentally for the onset of such extreme events, and as such, crises can be devastating to local residents (or others indirectly involved) in addition to direct victims of such events [3].

It is evident that bridge failures are unpredictable, meaning that we cannot give 100% assurance that a particular bridge will fail after 45 days from today and it is never going to happen that way. Early the national Government spend money on new infrastructures, right now we realise that, yes new infrastructure is something that we definitely need but we also need to take care of the old construction. With this in mind, the Ministry of Road Transport and Highways has earmarked close to ₹ 30,000 crores for about 1500 distressed bridges in our country.

Concerns of asset owners

In India asset owners of infrastructure systems - particularly bridges are generally the Ministry of Road Transport and Highways (MoRTH), the Ministry of Railways (MoR), State and Central Public Works Departments (PWD), National Highways Authority of India (NHAI), etc. The asset owner is always concerned with critical questions like

- How safe and healthy is the bridge?
- How long will it last? How long can I rely on it to be functional or when will it collapse?
- If it is at the end of its life, should I replace it or will a repair do a proper justice to this bridge?

These decisions are big ticket items because the cost implications of one decision as compared to any other may be huge. Unless we know the health of the bridge we cannot take the step to repair/replace or to predict how long it will last. For a decision to repair, these questions arise

- Do I need to repair again in after 10 years? or
- If the bridge has to last for the next 10 years, what kind of repair is needed?
- Is the repair scheme affordable?

These are the questions every asset owner has and there are no simple answers.

Gradual degradation with time

Mostly environmental effects cause a gradual deterioration which many a times goes unobserved. If some sudden shock comes, like an earthquake or tsumani, then off course we become aware of the distress to the bridge and some inspection is mandated. Today, in most situations, the inspection/repair/retrofit is adhoc, so we move our feet only when we get to hear about some distress or when there is a public uproar. In most of the cases, this doesn't work, meaning that it doesn't give us a cost effective solution. Many a times the money you are spending for repairing the bridge could well be put for replacing the bridge and constructing a new one (or say replace only a single span). Examples of cause of deterioration include corrosion, fatigue crack, loss of prestress, FRP strength reduction, etc. which are hardly noticed within a short time frame but the damage accumulates until a catastrophic failure occurs.

Due to this gradual degradation, the structural performance reduces over the life of a bridge. From a structural engineering point of view, the moment or shear carrying capacity decreases because rebar is corroding, and only the residual steel area will take the load demand. As long as the performance of such a degrading structure remains above a certain limit/threshold we are happy with the structure. Usually a large margin is kept between the design performance and the acceptable limit, in order to account for the lack of knowledge or a lack in the understanding of the actual behaviour. Over time, we slowly lose that margin and at one point in time the performance goes below the acceptable limit. At this point, we say that the bridge has reached its service-life, as shown in Fig. 1.

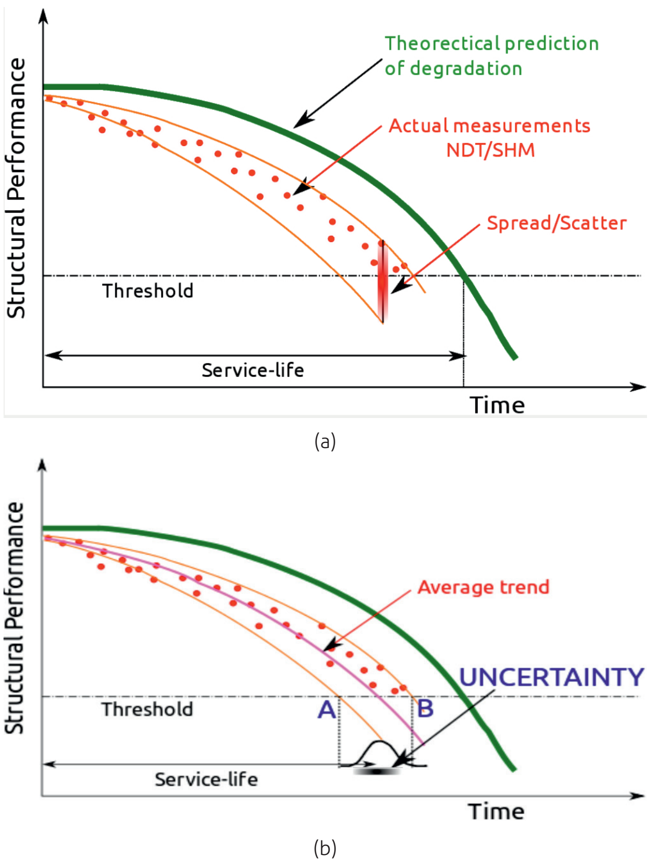

Figure 1: Deterioration with time

If NDT/SHM measurement of degradation is done in any real bridge, you will find deviation from the theoretical predictions [4], as represented in Fig. 1(a). Theoretical formulas, for example corrosion growth model [5], fatigue cracking equation [6], etc. are not very good predictors. These models work upto only a certain extent, because the reality of degradation is very complex to be modelled sufficiently through them. Additionally, the actual/real NDT/SHM measurements over time do not follow a perfect smooth trend, but rather they show an irregular pattern with a scatter as shown in Fig. 1(a). Thus, the structural performance has a scatter when we measure it, which can be represented by some bounds. What is the service-life now, should it correspond to the lower bound shown by point A or the upper bound shown by point B in Fig. 1(b). The estimated service-life will then have a spread. If we choose point A as the end of service-life, then we recommend that the bridge is going to collapse sooner. We are safe from the point of not having people getting killed from bridge collapse by stopping the functioning of the bridge at an earlier instant. For this decision, we may be incurring an excessive amount of cost in replacing or repairing that bridge. On the other hand, for B, the story is exactly the opposite. Initially we may be saving money, but there is some risk of casualty and economic losses. These things come into picture and so we say that there is an uncertainty in knowing the actual service-life shown in Fig. 1(b).

Erroneous decision making due to uncertainty on the bridge's current health and its future has the following consequences:

1. Unexpected (without warning) failure of bridge components
2. Unforeseen disruption in service
3. Unforeseen repair or replacement costs

Underestimation of the present health results:

4. Early replacement of a component; unnecessary repair cost

Sources of uncertainty

For the reasons of safety of people and protection of bridges, it is necessary to inspect and monitor degrading structures to evaluate and track their structural performance. In general, a structural assessment comprises: (1) collection of site-specific data, (2) structural analysis, and (3) decision making. Usually such an assessment is plagued with uncertainties associated with the collection and analysis of site-specific data such as [7]

- Inherent variability of the measured parameter: Degradation is not uniform, for example the amount of corrosion is never the same all over a bridge deck.
- Measurement errors: If the same quantity is measured twice by different engineers or using different NDT instruments, the result is never the same.
- Statistical uncertainty due to a limited number of measurements: Sufficient inspections are seldom possible due to constraint of time and money.

Thus, observations are usually replete with errors due to the imperfection in the instrument and the difficulty or impossibility in acquiring sufficient data [8]. Anyway, such inspection gives only the instantaneous condition of the structure and cannot be used independently for predicting its future degradation.

A maintenance/structural engineer is interested in predicting the trend of degradation of the infrastructure facility in the future. Engineers usually take the aid of models (mathematical and/or computational) to predict the behaviour of engineered systems. These models can be based on mathematical models of the effects of deterioration mechanisms and of the external actions, and/or from accelerated life testing, or a combination of both. However, the mathematical modelling of structural deterioration is a critical issue [9] because of the following reasons:

- Accelerated life tests often do not scale properly from the laboratory to the prototype or to the actual in-service conditions
- Many of the current models are empirical in nature and require experimental validation over the time scale of interest in performing condition assessment
- Synergistic effects of many Processes involved in degradation are seldom included in the limited supporting experimental data

Another important point is that the available deterministic models of deterioration fail to capture and model the scatter which is inherent as discussed earlier. Also the change in traffic load and changes in environment into the future cannot be predicted. On a different note, there are some elusive aspects which can escape the attention of even experienced designers and analysts because these never enter into the design considerations [10]. As a consequence, our knowledge about reality is imperfect. Fig. 2 shows a schematic representation of this 'path to imperfect knowledge'. In this figure, it is seen that due to uncertainty in models and in measurements we move away from the reality and end up taking decisions based on our corrupted knowledge. If we can quantify the uncertainty in our estimation, we should be very happy because based on this there are ways to calculate, what are the risks and consequence of a bridge failure.

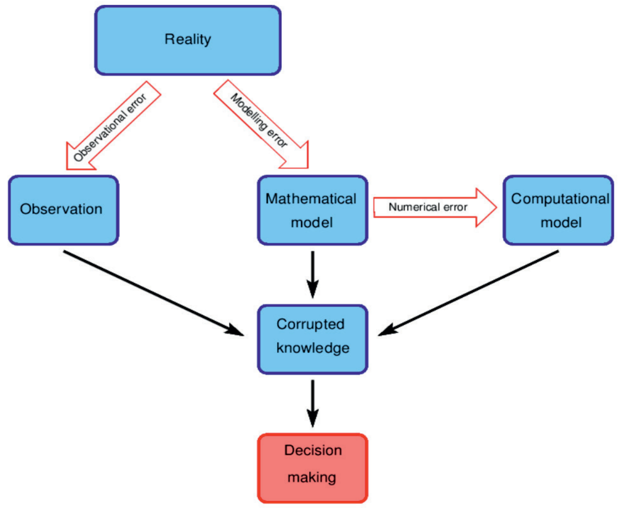

Figure 2: Path of imperfect knowledge

Our solution: change of approach

We acknowledge that uncertainty plays a major role in the deterioration process and our understanding of it. Neither the NDT/SHM nor the model can give an absolutely correct picture of the deterioration process. In order to be able to manage a degrading bridge over its service-life, it will be beneficial to combine the predictive capability of the theoretical degradation model and the data obtained from NDT/SHM [11]. Fig. 3 shows a schematic of the proposed solution. In Fig. 3(a), we see that there is a theoretical model, which is enhanced using the SHM data to arrive at the actual condition. We know that the actual prediction should not be a single curve shown in this figure, rather it should be a spread as shown in Fig. 1(a). Fig. 3(a) is just a representation of the average trend. Fig. 3(b) is more of a philosophical representation of the practical implementation of the concept. This figure shows accuracy of model versus its applicability. Here the applicability is inverse to the cost of the model, and we are averse to using costly alternative. The solid line shows that the more accurate model has less applicability, because more accurate models are costly. Our solution is that you learn based on your NDT and the solid curve translates to the dashed line. Previously more accurate models had low applicability. Since we have integrated information from NDT, now for the same level of applicability, we have higher level of accuracy (represented by the dashed line).

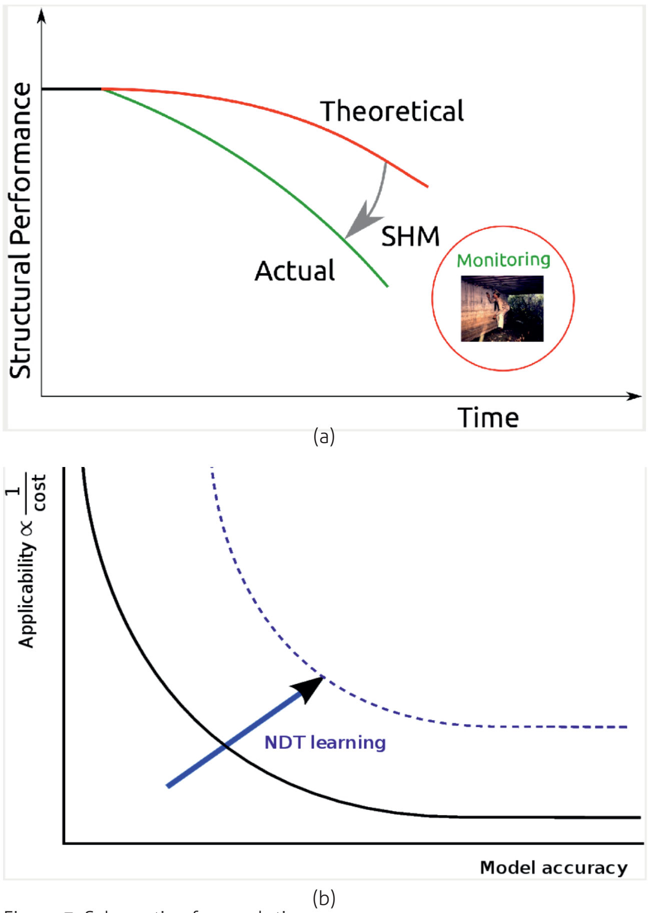

Figure 3: Schematic of our solution

However, because of the uncertain nature of the deterioration process and the inadequacy of any degradation model, it is necessary to setup the formulation in a probabilistic framework [1]. Further, proactive inspection instead of adhoc repair decisions help to timely detect and check the ageing process in time, and propose corrective actions to prevent structures, systems and components important to safety from ageing related faults/failures.

We have adopted a Bayesian technique to formulate the solution, comprehensively described in Ref. [2]. Fig. 4, for example shows the sequential updating of a corrosion growth model for a reinforced concrete girder. Each curve is colour coded with the text of the figure. NDT measurements are done at time instants t_1, t_2 and t_3. At each instant of measurement, the model is updated. When the next measurement is taken, the previously updated model is further updated with this measurement and so on. The updated model is used to predict the loss of steel at any later time instant. This prediction is in the form of a probability distribution which quantifies the uncertainties of the corrosion process, while giving the average trend, as well.

Service-life estimation

In order to demonstrate, the case of a corroding simply supported girder is considered. The updated distribution of rebar steel loss is used to compute the residual steel area and from this the distribution of mid-span moment capacity is evaluated. The probability of failure (P_f) can be computed for the limit state flexure failure. For civil structures, the acceptable annual exceedance probability of failure ranges in between 10^{-3} and 10^{-4}. For a probability of failure of 10^{-4} the service-life is considered terminated if the actual probability of failure exceeds this value. Fig. 5 shows the P_f plot over time based on sequential updating of the theoretical model using the NDT inspections of steel loss done biennially. The service-life is estimated to be 32 years.

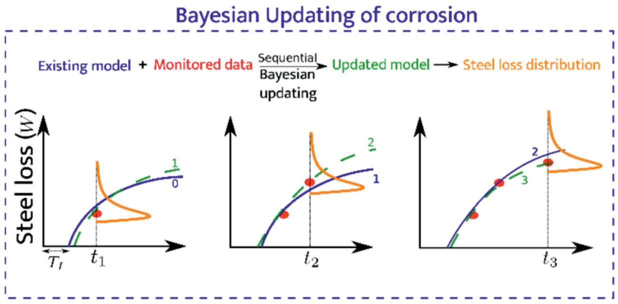

Figure 4: Updating model with NDT

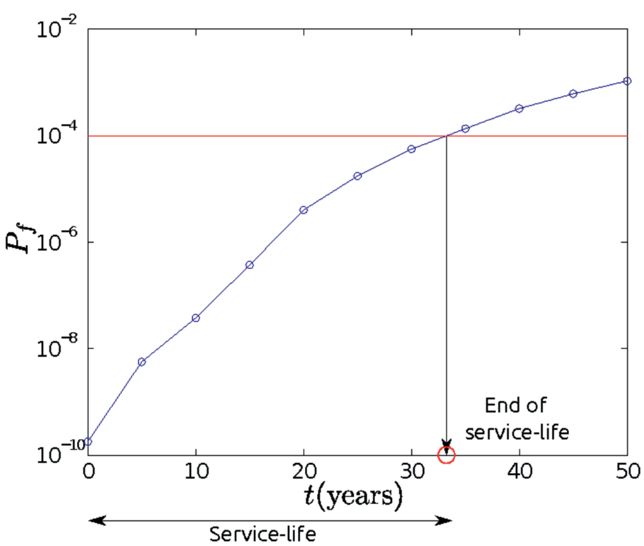

Figure 5: Time varying reliability of a corroding girder

Conclusion

This article introduces the challenges and deficiencies in the conventional assessment methods of degrading infrastructure. This comprises of uncertainty in the degradation model and in NDT measurement. However, this article also shows that there exists ways to solve this challenge through probabilistic formulation. An example of a corroding girder is shown and its service-life is predicted. The concept is also applied by the authors to combine gradual degradation such as corrosion with the effect of sudden damage such as, due to earthquake to compute the seismic fragility of a bridge pier [12].

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